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A Sensitive Search for Massive Long-Lived Particles

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Proposal Summary

We propose to make a very sensitive search for long-lived charged particles with masses $\geqslant$ 3 GeV. The proposed experiment should have a sensitivity about 10^6 greater than that of previous experiments at Fermilab. R. Cahn has suggested that the lowest mass particles with naked beauty may be stable If so, the proposed search may be the only hope of studying such particles until PEP, PETRA, or CESR are operational.

The experiment would make use of novel Cerenkov counters which only respond to relatively slow particles.

Purpose of the Experiment

Present limits for the production cross sections of massive charged particles from 300 GeV p-tungsten collisions are $\sim 10^{-7}$ those for pions at the same momentum and lab angle.[1] A limit $\sim 10^{-2}$ of the production cross section for ψ's has been placed on the cross section for production of stable neutral hadrons with masses ≥ 2 GeV.[2]

We believe that with a rather modest effort these limits can be improved by many orders-of-magnitude. A search for massive long-lived particles is especially timely now that it is clear that a new spectroscopy exists above 4.7 GeV. As Cahn[3] has emphasized, the lowest mass particles with naked beauty would be stable or long-lived if the b quark has little or no mixing with lighter quarks. The proposed experiment, which would place special emphasis on the mass region near 4.7 GeV, should be capable of finding particles with a production cross section $Ed^3\sigma/dp^3 \geq 10^{-39}$ cm^2/GeV^2 near $p_t = 0$ and $y = 0$. As discussed below, this is several orders of magnitude smaller than estimated production cross sections for particles with nonzero beauty. In view of the difficulty in finding naked charm at Fermilab, prospects for observing naked beauty appear very dismal unless a long-lived state exists.

Our search would also be sensitive to long-lived heavy leptons, another topic of great current interest. Massive charged leptons could be stable or long-lived if they do not mix with the lighter leptons and have a sufficiently massive "neutrino".

Another long shot possibility is that massive, stable, unconfined quarks with integral charge exist. This might be contrary to theoretical prejudices, but the only way to be sure they don't exist is to do the most sensitive search possible. The proposed experiment would improve present limits by many orders of magnitude.

Experimental Technique

The obvious problem in doing a sensitive search for massive particles is the background from copious production of π's, K's, and p's ($\bar{p}$'s). We propose to use Cerenkov detectors which would only be sensitive to particles with masses $\geqslant 3$ GeV. This would allow the use of a very intense beam with a corresponding increase in sensitivity.

The general features of the proposed Cerenkov counter design are shown in Fig. 1. The detailed design would depend somewhat on the beam line actually used. The index of refraction is chosen so that particles of the desired mass (say 5 GeV) have velocities somewhat over threshold. Cerenkov light from these particles is efficiently collected by the spherical mirror M_1 which, for particles with a given velocity, focusses the Cerenkov light onto a ring image at its focal plane near M_2. The radius of the ring image is proportional to the opening angle of the Cerenkov cone. This light is collected by annular mirrors M_2, M_2' ... and focussed to a spot on the face of photomultiplier tubes T, T', ...,[4] Cerenkov light from π's, K's, and $\bar{p}$'s goes off at much larger angles as shown. It strikes the blackened baffles on the walls of the counter and is efficiently absorbed. Several representative light rays are shown.

For the example shown in Fig. 1 we have used the following parameters:

$P_{beam} = 50$ GeV/c

$N_{photoelectrons} = 100\ \ell \sin^2 \theta$ (reasonable for a bi-aklali tube with a quartz face)

For a particle with mass 5 GeV, $N_{photoelec} = 36$

For a pion, kaon, or proton, $N_{photoelec} \cong 430$.

ℓ = length of counter = 400 cm

Diameter $\cong$ 45 cm

Index of refraction = 1.0055 (propane at approx. 80 psi)

An obvious question in the design is whether the more abundant Cerenkov light from low mass particles can be absorbed sufficiently well. The only way this can be answered is by testing a prototype. We believe the chances of success are excellent. The Handbook of Chemistry and Physics lists the reflection coefficient of carbon black in oil at 0.4μ as .003. Thus if the light made only a single bounce a pion would produce ~ 1 photoelectron. As is clear from Fig. 1, light from fast particles must make several bounces. With careful baffling and blackening of all surfaces except the mirrors we are confident that the design will work well.

The experiment would make use of at least four such counters, spaced as far as possible along the beam line. Pulse height and timing information from each would be digitized. By means of the pulse height information and timing with respect to the rf bunches we can distinguish massive particles with high redundancy. The counters accept a fairly wide range of masses, and we can cover the mass range 3 to 10 GeV with perhaps 5 beam momenta (or gas pressures).

The rejection of low mass particles is likely to be determined by how well Cerenkov light from secondaries and delta rays produced in the gas can be discriminated against. Several percent of the particles in the beam will interact in the counter. Most of the slower secondaries will go off at such large angles that the Cerenkov light will be absorbed in the baffling. For the fast forward particles the light will go off at too large an angle.[5] Pulse height requirements on the outputs of the phototubes should provide high rejection of interacting beam particles. Successive counters will be separated by large distances and bending magnets or quadrupoles so that rejection factors should be multiplicative. With the additional constraint that the time-of-flight for each counter be consistent with the mass assignment we are confident that sufficient rejection will be achieved. Tests of a prototype counter with beam will resolve most of the uncertainties before a full-fledged experiment is mounted.

Requirements on the Beam

Requirements on the beam are minimal. The main consideration is a large acceptance. The beam diameter at the Cerenkov counter positions should be $\leqslant 7$ cm and the divergence $<< 20$ mr. The counters would be ≈ 4 m. long. No other material would be placed in the beam so it would be available to other users simultaneously. When not in use the counters can be evacuated. We would need to exercise some control over the beam momentum during data-taking phases.

Choice of a suitable beam will be made in consultation with Fermilab staff. New beams in the Meson Area are likely to have the desired properties, but because PETRA is likely to be on the air within a year, we believe the experiment should be done as soon as possible. We would therefore prefer the high intensity pion beam in the Proton Area. In what follows we use that beam as an example, though with minor design modifications, other beams could be accomodated.[6]

In Figure 2 we show possible locations for the four Cerenkov counters in the high intensity pion beam. Table I shows times of flight relative to pions to each counter for massive particles with $\gamma = 10$. Expected resolving times are ~ 1 ns (Refs. 1 and 2) so these flight time differences are sufficient to give good rejection, except possibly for the first counter.[6]

Estimate of Ultimate Sensitivity and Running Time Requirements

According to the Design Report for the P-West High Intensity Secondary Beam,[7] for 400 GeV running the beam should be capable

Table I - Possible Positions for Counters in High Intensity *Beam Line* and Time-of-Flight (rel. to photons) of Particles* with γ = 10

Counter	Distance from Target	Δt (ns)
I	320'	1.6 ns
II	485'	2.4 ns
III	555'	2.8 ns
IV	720'	3.6 ns
V	(?)	

*These positions are based on beam characteristics given in the March 1977 Design Report (with sextupoles off). The positions actually used will depend on the beam properties when the experiment starts and may depart considerably from those given. The main considerations in the choice of locations is that the transverse dimensions of the beam be sufficiently small and that the counters be well spaced along the beam line.

of providing approx. $4 \times 10^9\ \pi^-$ at 50 GeV/c with 10^{13} interacting protons. For our estimates we assume $\sim 10^9\ \pi^-$ per pulse. With 100 hrs. of running for each mass interval, the number of π's passing through the counters will be

$$\sim 10^9\ \pi/\text{pulse} \times 300\ \text{pulses/hr} \times 100\ \text{hrs} = 3 \times 10^{13}\ \pi^-$$

Assuming our rejection of pions is adequate, we would then be sensitive to massive particles with production cross sections $\gtrsim 10^{-13}$ that for pions at the same lab momentum and angle. This would be at least six orders of magnitude more sensitive than the experiment of Appel et al.[1]

To compare this with plausible estimates of cross sections for producing stable particles associated with the Υ, we can use data for dimuon production in the Υ region. For $p_T \approx 0$ and $y \cong 0$, D. Kaplan *et al.*[8] give

$$B(E\, d^3\sigma/dp^3) \approx 10^{-37}\ \text{cm}^2/\text{GeV}^2$$

where B is the branching ratio to muon pairs. As a guess we take $B \sim .05$ to get a production cross section

$$(E\, d^3\sigma/dp^3) \sim 2 \times 10^{-36}\ \text{cm}^2/\text{GeV}^2$$

If the Υ is the "onium" state of a b and $\bar{b}$ quark, low mass particles with naked beauty should be produced with comparable cross sections.

From Ref. 1, the production cross section for π^- with $p_T = 0$ and $p_{lab} \approx 50$ GeV/c is $(E\, d^3\sigma/dp^3)_\pi \approx 10^{-26}\ \text{cm}^2/\text{GeV}^2$. Our projected limit of 10^{-13} times the pion production cross section corresponds to an invariant cross section $\sim 10^{-39}$ cm^2/GeV^2, or a factor of 2000 smaller than the estimated cross section for producing naked beuty!

Scheduling

Our specific running time request is the following:

(1) Sufficient time in a test beam to optimize the Cerenkov counter design

(2) 200 hours of testing time in the actual beam line on a parasitic basis

(3) 500 hours of running time for data taking ($\approx$100 hours per mass interval). During this time beam will be available to other users.

Immediately upon approval of the experiment we would start building a prototype counter. Building and testing should take < 6 months. Assuming the tests are a success we would be ready to set up about 9 months after approval.

Costs

We would provide the Cerenkov counters. The laboratory would provide the beam and appropriate controls and diagnostics (SWIC's) for beam tuning. We would request fast electronics from PREP. Michigan would provide the computer for data acquisition. Costs to the University of Michigan would be borne by a continuing NSF grant.

References and Footnotes

1. J.A. Appel *et al.*, Phys. Rev. Letters 32, 428 (1974).

2. H.R. Gustafson *et al.*, Phys. Rev. Letters. 37, 474 (1976).

3. R.N. Cahn, Phys. Rev. Letters 40, 80 (1978).

4. Mirrors M_2, M_2', ... are annuli sliced from an ellipsoid by two parallel planes which are approx. 45° to its axis of rotation.

5. Cerenkov counters of conventional design would also have to cope with a comparable background from interactions in the gas. They would, of course, be limited to much lower beam levels if the light from pions is collected.

6. One disadvantage of the high intensity pion beam is that it is rather short so that time of flight differences are uncomfortably small unless relatively low momenta are used. For this reason we have used a design momentum of 50 GeV/c for the mass interval centered at 5 GeV/c^2. For other mass intervals the optimum beam momentum is proportional to the mass (e.g. - 100 GeV/c for 10 GeV/c^2 masses).

7. Intensity estimate updated by C.T. Murphy, 1/16/78.

8. D.M. Kaplan et al., Fermilab - Pub. 77/107 EXP, submitted to Phys. Rev. Letters (Dec. 1977).

CERENKOV COUNTER DESIGN

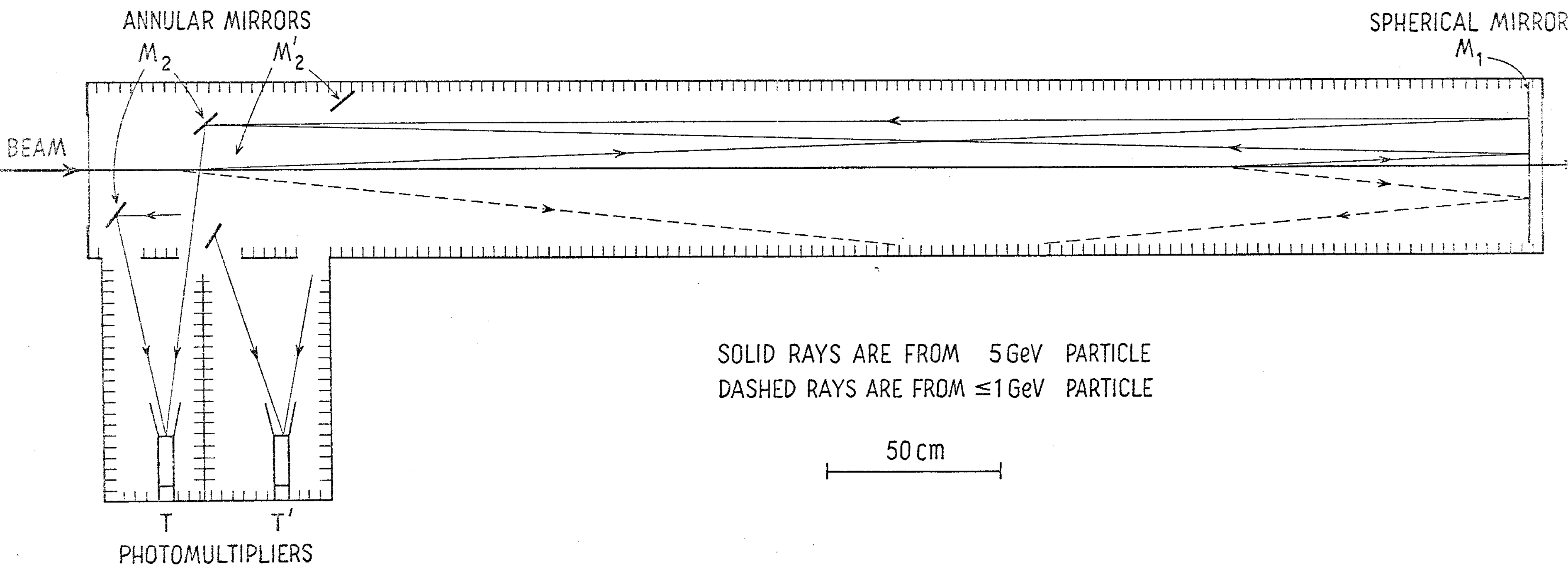

Figure 1

P-West High Intensity
Secondary Beam

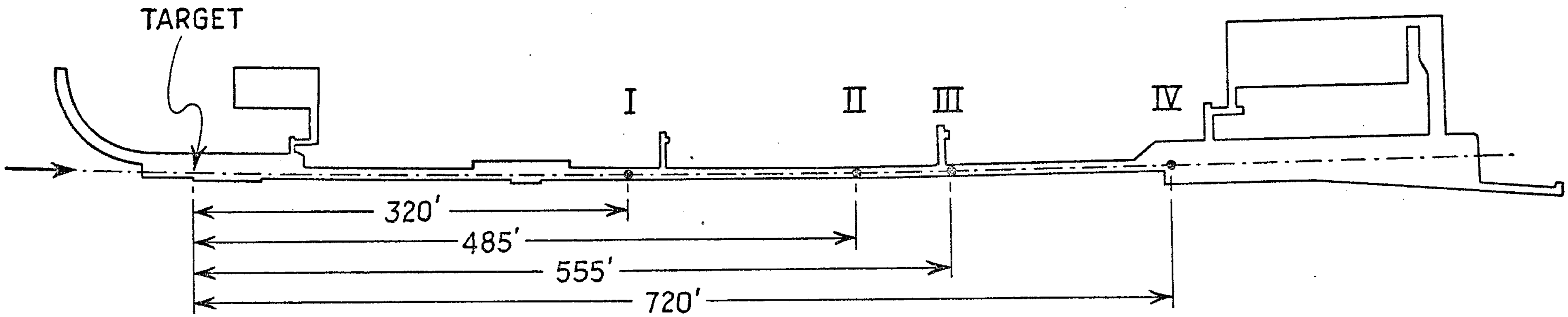

Figure 2